Commentaries

On the Use of Units in LCA

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Introduction

Almost every respectable scientific journal has a statement on the use of units included in the *Instructions to authors*. Int J LCA provides the following statement (http://www.scientificjournals.com/sj/pdf/lca/autorenhinweise.pdf):

> **Units:** Use only metric units (SI) and some other units listed in ISO 1000. Examples of such additional units, not belonging to SI, are hectare (ha), litre (= dm³) (l, L), day (d), hour (h), minute (min), km/h, tonne (= Mg) (t), Wh and its multiples, as kWh, MWh, GWh (only in order to distinguish electrical energy from other forms of energy), decibel (dB), mol/l or mol/L (= mol/dm³), electron volt (eV) and its multiples, as keV, MeV, GeV. The degree Celsius (°C) belongs to SI with the definition that zero degree Celsius is equal to (exactly) 273.15 K.

Browsing through recent issues of this journal, however, shows that there are quite a few papers that express results in units which are apparently not allowed: kg CO_2-equivalent, DALY, ELU, and the like. It is the purpose of this commentary to stimulate awareness and discussion on this issue – among authors, referees and editors – to be precise with units. The results of a critical examination of the use of units may give LCA a more scientific appearance and is indispensable when establishing a best available practice for LCA.

Some Historical Background

Units have been introduced in measurement schemes to express quantitative properties. Basically, any quantity, such as the distance between Paris and Moscow, can be expressed in many ways. It is the adoption of the unit of measurement, in this case for length, that enables us to communicate such quantities. The choice of this unit of measurement is flexible. Historically (see Klein 1974), this has led to a profusion of units, from the Roman stadium to the Finnish jalka. Nowadays, the choice has been reduced to a handful, including the metric metre, the British yard and the American mile.

For scientific and technological purposes, and also for commercial ones in the age of globalization, a further standardization has been achieved by the *General Conference on Weights and Measures*, held in Paris in 1960, which gave birth to the *Système International d'Unités*, abbreviated as SI. The SI is regularly updated; the current version is the 7th edition of 1998 (Anonymous 1998). The SI distinguishes seven base units: the metre, the kilogram, the second, the ampere, the kelvin, the mole, and the candela, as well as a number of derived and supplementary units. It also provides standardized symbols for abbreviating these units (like m and kg), and encompasses the system of prefixes (like mega and milli). On top of that, the SI recognizes a number of derived units, like m² and kg/m³, some of which have received special names and symbols, like the newton (1 N = 1 m·kg/s²); derived SI units may again be used to derive other units, like the N/m. Finally, a few units 'outside the SI' are recognized as temporarily acceptable for scientific, technological or commercial purposes. These include the hour, the litre, the bel, the hectare and the calorie.

The SI has been translated and adapted according to the needs and historical settings of national scientists. Most importantly, the ISO 1000 International Standard (Anonymous 1992a) and the US National Institute of Standards and Technology (Taylor 1995) have provided interpretations, elaborations and practical examples. Especially this last reference also provides other recommendations such as on the use of ppm and the incorporation of units in sentences of text.

In its conception, the SI is apparently biased towards the physical sciences. While there is a unit for light intensity (the candela), there is, for instance, no unit for money, illness or biodiversity. It is natural that discourses outside the physical sciences propose and develop additional units to be able to measure, compare and communicate quantities in those disciplines. Even the physical sciences have designed and still design new units, sometimes because the SI-unit is too impractical (hence the ångström), sometimes for historical reasons (like the degree celsius), and sometimes to express more complex quantities (as for the (deci)bel). Historically, the introduction of new units has not always been welcomed. The need for a unit for frequency, the hertz, has sharply been doubted in the 1920s.

Social and behavioral sciences fell outside the SI from the outset. So called Likert scales are a normal device for expressing preferences, attitudes or behavior on a 5- or 7-point scale. Points on these scales bear meaning like 'strongly disagree' or 'very often'. They are essentially ordinal scales, for which the algebraic operations like addition and multiplication do not make sense. It is a complication that they are often used like that, for instance by calculating the respondents' mean preference, which falls outside the present scope. For the purpose of this commentary it suffices to say that the social and behavioral sciences have devised ways to express subjective judgements on quality in a way outside the SI-scheme.

Units, Dimensions and Quantities

There may thus be good reasons to introduce new units in LCA. However, such an introduction is not trivial. Some background in the theory of measurement is needed to ensure consistency. This section surveys some basic principles.

James Clerk Maxwell starts his monumental *Treatise on Electricity and Magnetism* (first published in 1873) with a 'Preliminary on the Measurement of Quantities.' The first paragraph reads as follows:

> Every expression of a Quantity consists of two factors or components. One of these is the name of a certain known quantity of the same kind as the quantity to be expressed, which is taken as the standard of reference. The other component is the number of times the standard is to be taken in order to make up the required quantity. The standard quantity is technically called the Unit, and the number is called the Numerical Value of the quantity.

Here, we see a clear statement of the basic idea of measurements:

Quantity = Numerical Value * Unit

A simple example is:

Distance = 1200 * kilometer

Another example is:

Height = 1000 * foot

(The multiplication sign '*' is almost always left out.) Here, we immediately see that these two examples have something in common, even though they seemingly differ in every aspect. What they have in common is that they both are about lengths. A distance is a length, and so is a height. And both kilometer and foot are units of length. This common aspect, length, is referred to as the dimension of distance and height, and kilometer and foot are examples of units for this dimension.

As said above, the SI is constructed around seven basic units. These are supposed to belong to seven basic dimensions: length, mass, time, electric current, temperature, amount of substance, and luminous intensity. Combinations of these dimensions can be described with combinations of the associated units. Thus, velocity, has the dimension length divided by time, or $[LT^{-1}]$. It can be expressed in meter per second, kilometer per hour, or any other valid combination of units for length and time. For practical purposes, we may wish to define a new unit, such as the benz instead of 1 meter per second. And, when the basic dimensions are insufficient, additional dimensions must be introduced, with accompanying units. Economists (see De Jong 1967) have defined the dimension money, with a range of units: dollar, euro, yen, and so on. It allows you to specify of number of quantities like price and debt. It can also be used for compound dimensions, for instance in expressing a wage in dollar per month.

A special case of a dimension is that of a quantity having no dimension. Many ratios and fractions are dimensionless quantities. For instance, a product of 1 dollar with an added tax of 20 cent can be said to have a tax rate of 0.2 (or 20%). A problem of a dimensionless ratio is that one cannot see of what this quantity is a ratio. The problem notoriously shows up in alcohol percentages, which can be based on the mass ratio or the volume ratio. From a mere 5%, one cannot tell if it is a volume percentage or a mass percentage. There are two solutions to this: either adding the word 'mass' or 'volume' to

the %, or agreeing on the precise definition of the quantity, so that the numerical value unequivocally refers to a well-defined meaning. The problem occurs also for non-dimensionless quantities. Soil chemists and toxicologists know very well that many quantities can be expressed 'per kg of wet soil' or 'per kg of dry soil'. Instead of making this part of the unit, one could also agree on the definition of the quantity, which allows, by definition, the formulation 'per kg' (of dry soil). Indeed, Taylor (1995) explicitly discusses this case and writes: the form 'the water content is 20 mL/kg' is used and not '20 mL H_2O/kg' or '20 mL of water/kg' Taylor (1995, p.v).

In all cases, we need to distinguish three concepts:

- the quantity that is to be expressed;
- the dimension of that quantity;
- the unit or units chosen as the standard of measurement for that quantity.

For example, when we say that a substance has a half-life of 5 days, we are talking about a quantity, called the half-life, which has the dimension of time, and for which the day is an appropriate unit.

Examples in LCA

Let us now move back to LCA, and in particular to *The International Journal of Life Cycle Assessment*. The inventory analysis is concerned with flows of products, materials, substances and energy, and for them, the physically-based SI appears to be sufficiently practicable. Things are, however, different as to the impact assessment. Here we see impact categories like climate change, damage categories like human health, as well as normalization and weighting. We are no longer talking of quantities for which a physical measurement can be performed, but of quantities that are subjective and have an inherent notion of quality or severity. No appropriate SI units are available to express these quantities.

Take the first three issues of the most recent complete volume of the journal, volume 9, and browse through the theoretical papers on LCIA or the case studies that include the LCIA-phase. We discern three groups of problems:

- related to the use of potentials, like GWP;
- related to the use of human health damage, like DALY;
- related to the use of weighted and aggregated indices, like Eco-indicator 99.

I will illustrate and discuss these below. Moreover, I will discuss not only the aspect of unit, but also that of dimension and quantity.

Example 1: The use of potentials

Most authors appear to agree that greenhouse scores are to be expressed in kg CO_2-equivalents. So, kg CO_2-equivalents are generally regarded as the unit. This is not a strict SI-unit: the kg-part is, but the specification 'CO_2-equivalents' is not. However, it may be considered as the 'per kg of wet soil' type, as a specifier of a measurement definition. But then, what does it measure? Andræ et al. (2004, p. 49) quote it for 'Greenhouse Warming Potential', Jiménez-González et al. (2004, p. 118) for 'greenhouse gases emissions (GHG)', Schmidt et al. (2004, p. 128) for 'Global warming', and Fröling et al. (2004, p. 134) for 'GWP'.

The global warming potential or GWP is indeed a quantity, not a dimension or a unit; see Houghton et al. (1990, p. 58). But it is a quantity that is a fixed substance property, determined by a model, like the IPCC-model. For instance, the GWP of CO_2 is 1, and for CH_4 it is 21. It is calculated with complex atmospheric models, but it is never calculated in an LCA-study. It is used like the density or the specific heat of a substance: a per-kg fixed property that is multiplied with the actual amount of substance to obtain the mass heat capacity of the object of concern. In LCA, one multiplies the GWP with the mass emitted to obtain the infrared radiative forcing of the product life cycle of concern. As this infrared radiative forcing is said to be the impact category indicator for global warming or climate change (hence to indicate it), one can say that the global warming or climate change of a product life cycle is calculated in an LCIA. The GWP itself is a characterization factor.

Next the dimensions and units. The GWP of greenhouse gas is a dimensionless ratio. It thus needs no unit, although it is quite normal to define it to be 'kg CO_2/kg greenhouse gas'. Multiplication with the inventory result, in 'kg greenhouse gas', yields 'kg CO_2', which is often quoted as 'kg CO_2-equivalent'. A plain 'kg' would also do, because the explicit summation rule is about kg of greenhouse gas. In any case, the dimension of global warming or climate change is mass. In fact, given the recommendations from experts in the field of units (e.g. Taylor 1995), no qualifiers should be used after the unit, hence one should use 'kg' instead of 'kg CO_2-equivalent'.

In reported LCAs, the same problem appears for other impact categories and characterization factors, like ODPs, HTPs, and the like.

Example 2: The use of human health damage

Endpoint-oriented methods for LCIA, which assess human health, almost invariably use the DALY approach. But they do this in many different forms. Itsubo et al. (2004, p. 202) use DALY as a unit: global warning causes '9.49E+4 DALY'. The same is applied by Müller-Wenk (2004, p. 83), who even speaks about 'DALY units'. On the other hand, Itsubo et al. (2004, p. 200) use DALY as a damage indicator, with the dimension 'Year'.

The DALY-concept stems from an attempt to combine mortality (years of life lost, YLL) and morbidity (years of life disabled, YLD) into one overall measure: disability-adjusted life years, or DALY (Murray and Lopez 1996). The very fact that the 'Y' stands for 'year' suggests that DALY is a kind of unit. So, what about

damage = 12 DALY

But DALY is definitely not an SI-unit, while we have a perfect SI-unit for time[1], which would suggest

damage = 12 year

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[1] One small complication should be mentioned: the SI does not officially recognize the year as a valid unit for time. It recommends the second (s) as the principal unit, with the minute (min), hour (h) and day (d) as alternatives. The problem of the year, is that there is no unambiguous year. One might choose 1 year = 365 d, or 365.25 d, or a more astronomical inspired form, such as the siderial year (365.256 d) or the tropical year (365.242 d), which are moreover not constant over the centuries. The only ISO standard on metrology that mentions the year is ISO 31-1 (Anonymous, 1992b), which abbreviates the tropical year with the symbol 'a'.

But then, the DALY has disappeared. One might try it as a quantity, like in

DALY = 12 year

This has the strange feature that the quantity is termed in its unit. This is strange, for we know that length can be defined independent of our preference for meters. It would be somewhat weird to state that

DALY = 4380 d,

although this is perfectly compatible with the ordinary operations of changing the unit. A possible solution is to consider 'DALY' as a variant of 'kg CO_2-equivalent'. If we make clear that these kg are special kg, namely 'kg-CO_2E', we make clear that the yr are special: 'yr-DAL'. For some historical reason, the form 'DALY' has been chosen.

Then: what do these special years indicate? They are supposed to be the unit of an indicator for damage to human health, which hence is the quantity at stake.

Similarly to the DALY for human health is the PDF or PAF for ecosystem health. These stand for potentially disappeared (or affected) fraction of species, which sound like a dimensionless quantity. Some authors integrate PDF over a surface and express the result as PDF*m^2. When PDF is considered as a quantity, this obviously mixes up quantity and unit. The quantity would have to be 'surface-integrated PDF', with the unit 'm^2'.

Example 3: The use of weighted and aggregated indices

Weighting in LCIA refers to the act of assigning weighting factors to impact categories and to apply these to the previous results, at the midpoint level, at the endpoint level, or normalized. Andræ et al. (2004, p. 49) quote results for Eco-indicator 99 in 'Millipoints', and (p. 50) for EPS in 'ELU'. In contrast, Fröling et al. (2004, p. 134) express results for EcoIndicator99 and Ecoscarcity in 'Ecopoints'. These 'points' and 'units' are much outside SI, and their origin and meaning should be investigated.

Most methods for impact assessment which include a weighting into a single score also include normalization as a prior step. Category indicator results such as global warming (in kg) or damage to human health (in year) are divided by a reference situation: the magnitude of these indicators for a certain region in a reference period, like Europe in 2002. As this reference period is a temporal quantity with the dimension of time, the reference situation can be described in terms of global warming (in kg/year), damage to human health (in year/year) and so on. Dividing a characterization result by these reference values, yields normalized results for global warming (in year), damage to human health (in year), and so on. Thus, the resulting quantities of the normalization have the dimension of time.

A subsequent weighting step multiplies these normalized results by weighting factors. These weighting factors may be derived from various sources:

- they may be assigned by a panel that was supposed to distribute 100 points among all impact categories,
- they may originate from distance-to-target considerations,
- they may be revealed from budget decisions in terms of the fraction of money spent to a certain problem, etc.

In all these cases, the weighting factors are dimensionless quantities.

Multiplying a normalized result (in year) with a weighting factor (dimensionless) yields an aggregated index, with the dimension of 'year'. The ecopoints and millipoints derived from normalized scores are thus simply a year or a milliyear. For the ELU of EPS, a somewhat different argument holds. The ELU corresponds to a EURO of monetized damage. Although there is no monetary unit in the SI, the EURO is a widely accepted unit of currency, whereas the ELU is not a widely accepted synonym.

Standardization of symbols

The SI provides a standardization of units. It also provides a standardization of the writing of units (for instance, the use of small letters for the full word and the removal of diacritic signs, like 'ampere' instead of 'Ampère'), as well as their abbreviation (hence 'N' for newton). But it does not provide a standardization of the symbols that are to indicate the quantities. A distance may be indicated as 'x', as 'd', as 'dist', and so on. The same applies to LCA. Although we should express global warming or climate change in 'kg', there is no standardized symbol for abbreviating global warming or climate change. One may use 'GW' or 'CC', or define any other convenient symbol. For many characterization factors, there is a standard, set by the authors of the equivalency principle. Thus, 'GWP' is used for global warming potentials, 'HTP' for human toxiciy potentials', and so on.

Conclusion

The results of the critical analysis is summarized in **Table 1**.

Although some familiar terms (like kg CO_2-equivalent, DALY and mPt) do not appear in the proposed set-up, the elegance culminates in a perfect harmonization with the SI. Conformity with the SI is, whenever possible, a *conditio sine qua non* for scientific maturity.

> The analysis presented cannot claim to be the final truth. I welcome critical comments to these proposals, with the intention of establishing, as part of the best available practice of the UNEP/SETAC Life Cycle Initiative, a table of best available quantities, dimension, and units for LCA.

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Table 1: Summary of the critical analysis of the application of units used in LCA

Name of quantity	Dimension	Preferred unit	Use in LCIA
global warming potential or GWP	dimensionless	– or kg/kg	characterization factor
global warming or climate change	mass	kg	category indicator result (midpoint)
human health damage	time	year	category indicator result (endpoint)
ecosystem health damage or PDF or PAF	dimensionless*	–*	category indicator result (endpoint)
normalized result	time	year	result of normalization step
weighted index	time or money	year or euro	result of weighting step
* Sometimes: area with unit m²			